Time-Domain Simulations of Problems in Ocean Acoustics

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LONG-TERM GOALS

To develop time-domain numerical methods for the study of propagation and scattering of acoustic and elastic waves in the shallow water environment.

OBJECTIVES

To develop new, and enhance existing, numerical methods; to establish the accuracy, robustness, flexibility, and tractability of these methods; and to apply these methods to meaningful practical problems. To create a robust software suite for the application of the methods and to develop techniques for visualizing the propagation of scalar and vector fields in complex environments.

APPROACH

We have focused our attention on the development and use of finite-difference time-domain (FDTD) methods. Various forms of these time-domain techniques, which are flexible, robust, and generally simple to implement, have been used in a variety of disciplines to solve a wide range of problems. We have worked, and continue to work, to establish the accuracy of our proposed acoustic FDTD techniques by comparing numeric results to exact solutions for canonical problems or to results obtained using other numerical methods.

WORK COMPLETED

Equations were derived which rigorously codify the propagation of fields in FDTD grids. These equations were then used to construct a nearly perfect total-field/scattered field boundary (which is used to inject energy into the grid). Initially this work was restricted to a homogeneous medium which surrounds an arbitrary inhomogeneous medium. This work has subsequently been extended to layered media. This required the derivation of the numeric reflection and transmission coefficients which pertain to the FDTD grid. Further extensions to the theory now permit incident grazing angles less than the critical angle, lossy media, and the insonification of semi-infinite structures (such as wedges).

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RESULTS

The FDTD method is obtained by discretizing the differential equations that govern the underlying system. Using a Cartesian grid, the method provides an exceedingly simple way in which to express future fields (i.e., unknown fields) in terms of past fields (known fields). For propagation in a homogeneous region, the traditional FDTD method is accurate to second-order—that is, doubling the number of grid points per wavelength reduces inherent numerical errors by a factor of four.

The behavior of fields and accuracy of the FDTD method at material interfaces are much more complicated than in a homogeneous region. We previously derived exact expressions describing the behavior of plane waves at planar boundaries [1,2]. Our previous work considered normal incidence and has recently been extended to oblique incidence [3]. The derivations in [3] show rigorously what has long been assumed in practice: that the optimum density for nodes along the interface is the average of the densities to either side.

Additionally we have examined and developed ways to minimize the errors associated with the "stairstep approximation" which is inherent when modeling continuously varying surfaces in the FDTD method [4-9]. The work recently published in *The Journal of the Acoustical Society of America* showed how employing a simple modification of the equations used to updated the fields adjacent to a rigid boundary could significantly improve the accuracy of the simulation [9].

Our investigations of the discretized worlds of FDTD methods have led us to a better understanding of numeric artifacts associated with resonances and to ways of alleviating these artifacts. Part of this work was presented as an invited talk in a special session organized by Prof. Allen Taflove (one of the co-founders of the FDTD method) [10]. This work is further described in a paper which has recently appeared in *IEEE Transactions on Antennas and Propagation* [11]. In that work we show how the anisotropic dispersion inherent in the traditional "Yee" FDTD algorithm can cause rather bizarre behavior in the resonant modes of a canonical resonator. Modes which are degenerate in the continuous (or "real") world can split into multiple modes. On the other hand, modes which are distinct in the continuous world may be degenerate in the discrete FDTD world. Additionally, even modes that are not split or recombined in some spurious manner in the FDTD world can nevertheless be shifted from the true resonant frequency that pertains in the continuous world. Our work provides a way to quantify this behavior exactly without ever needing to perform an FDTD simulation.

Given this understanding of the traditional FDTD technique, we were motivated to explore a technique which was more isotropic than the traditional FDTD technique. Thus, we developed a variation of the promising FDTD scheme proposed by Eric Forgy (*IEEE Transactions on Antennas and Propagation*, **50**(7):983–996, 2002). This algorithm suffers much less grid dispersion and anisotropy than more traditional FDTD formulations but still retains the local nature of the standard update equations. The acoustic implementation of this algorithm was described in a paper which recently appeared in the *Journal of Computational Acoustics* [12].

The Yee FDTD algorithm can provide exact solutions to one-dimensional problems when operated at the so-called magic time step (i.e., when the spatial step size is equal to the speed of light times the temporal step size). Here "exact" is taken to mean the field propagates without dispersion error or other numeric artifacts beyond those which are dictated by the finite precision of the computer. Unfortunately there is no magic time step in higher dimensions. However we have recently developed a theoretical framework for multi-dimensional algorithms that have the same exact properties as the one-dimensional Yee algorithm when operated at a particular time step. The proposed technique uses vector operators which, instead of being defined at a point such as with the usual gradient, divergence, and curl operators, are defined over spheres. Due to their inherent symmetry, these spatial operators have the same properties in all directions. With a judicious choice of the temporal step size the temporal errors can cancel the spatial errors and the algorithm is exact. However, although the framework for the algorithm has been developed, no practical (i.e., computationally efficient) algorithm has yet been developed. It should also be noted that the method is only theoretically exact on an infinite grid—a finite grid will introduce some inherent error but that error will be smaller than traditional FDTD techniques. Nevertheless proof-of-concept implementations of the algorithm (which are quite computationally expensive) have been used to demonstrate the validity of the technique and the improvements the algorithm can provide over other FDTD implementations. The algorithm also has interesting properties such as unconditional stability for an arbitrary temporal step size. Some of our work on this algorithm was presented as an invited talk at the 2003 URSI/Antennas and Propagation Symposium [13]. This work is further described in a recent publication in the *Journal of Computational Physics* [14] and a Ph.D. dissertation [15] (the author of which was partially supported under this grant).

The understanding we have obtained of the FDTD method has provided a complete quantification of the way in which plane waves propagate in the discrete FDTD world. Using this knowledge we were able to construct an enhancement to the total-field/scattered-field (TFSF) boundary, which is a boundary used to introduce field into the FDTD grid. This enhancement, which is nominally exact, can provide an enormous improvement over the traditional implementation (better than a 100 dB reduction in errors in many situations). This work is described in a paper recently published in *IEEE Transactions on Antennas and Propagation* [16]. Additionally Prof. Taflove invited the PI to contribute a section [17] to the 2005 edition of his FDTD book [18] which has come to be regarded as the authoritative source for FDTD-related information.

Our work on the implementation of TFSF boundaries has been extended to layered media—either rigid, pressure-release, or penetrable boundaries. This work is described in [3]. The capabilities this technique provides opens many new avenues of investigation. For example, the scattering from rough surfaces can be explored without having to resort to using Gaussian-tapered plane wave excitation (which is only an approximate solution to the wave equation) which was used in [19,20]. Furthermore, the scattering from semi-infinite objects (such as wedges or screens) is easily accommodated as described in [3].

We continue to expand the capabilities of our TFSF implementation. We have developed an efficient implementation for 3D problems in which the incident direction is orthogonal to one of the grid axes. The technique can also handle lossy materials and the incident angle may be sub-critical.

We continue to maintain a Web site, `www.fdtd.org`, that seeks to list all archival publications related to the FDTD method. This site solicits input, in the form of comments posted about work appearing in the archival literature, from the entire community interested in the FDTD method (whether applied to acoustics, electromagnetics, or solid mechanics). We have also made code available there which can be used to solve various propagation problems.

IMPACT/APPLICATIONS

Accurate and flexible numerical methods allow researchers to conduct any number of experiments without having to resort to actual field experiments, i.e., the experiment is conducted on the computer. Our work enables more accurate and more efficient numerical solutions to a wide range of problems in acoustics, electromagnetics, and continuum mechanics.

TRANSITIONS

Much of the knowledge we have gained has been disseminated via publications and conference presentations. Additional material is available via the Web. Please refer to the Web site given in the header for copies of the PI's publications or `www.fdtd.org` for other material pertinent to the FDTD method.

RELATED PROJECTS

This work is related to research in both high-frequency acoustics and long-range propagation. Numerical models, such as the FDTD method, can be used to predict the fields scattered from small objects under short-wavelength insonification or the propagation of long-wavelength signals over limited regions of the ocean. This work is related to that being done by several other ONR-sponsored researchers.

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